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Abiotic Resource Depletion

Different perceptions of the problem with mineral deposits

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Abstract

Background Aims and Scope. Access to abiotic resources is vital for modern life styles. Except for ozone depletion, no other environmental threat has a potentially larger impact on our everyday lives than shortage of abiotic resources. In 'Limits to Growth' the Club of Rome identified depletion of ores and minerals as becoming a major problem during the first or second decades of the twenty-first century, and the idea was widely spread. Since then, the attitude to the problem has shifted, and many institutions, such as the European Commission, do not consider the problem acute and does not give it priority in their present action plans. Regardless of when it happens, however, the social consequences of a shortage of abiotic resources will be a major problem and the significance and nature of the problem will depend on what the world looks like then at the time and afterwards. This article discusses existing LCIA methods in relation to their views on the depletion problem.

Method. Review of existing LCIA methods in relation to depletion problem definitions.

Results and Discussion. Existing methods for characterisation and weighting of abiotic resources appear to be based on four types of problem definitions, although not always explicit: 1) assuming that mining cost will be a limiting factor, 2) assuming that collecting metals or other substances from low-grade sources is mainly an issue of energy, 3) assuming that scarcity is a major threat and 4) assuming that environmental impacts from mining and processing of mineral resources are the main problem. In addition to differences in assumptions about what will be the limiting factor, there are different views on what time scales are of interest and how to integrate the issue in LCA.

Conclusion. The main dividing line in views on abiotic resources has to do with time perspective. If only caring for the next hundred years or so, abiotic resources is a manageable problem. In taking an historic perspective with tens of thousands of years, abiotic resources become a major problem.

Recommendations and Outlook. Today there seems to be some consensus on focusing on developing characterisation methods based on future increase of impacts from using lower grade resources with consideration of resource functionality. It is essential that the choice of temporal focus is given enough attention.

Keywords: Abiotic resources; category indicator; cost; energy; exergy; impact category, indicator, LCIA, minerals; scarcity

Introduction

Access to abiotic resources is vital for modern life styles. Except for ozone depletion, no other environmental threat has a potentially larger impact on our present everyday lives than a shortage of abiotic resources. Without abiotic resources, there would be no food, no cars, no comfortable indoor climate, no efficient health care, etc.

In 'Limits to growth' Meadows et al. (2005) identify the increasing cost of resources as becoming a major problem for society during the first or second decade of the third millennium and their ideas were widely spread. Since their first version in 1972, written for the Club of Rome, the general attitude to the problem has shifted, and many institutions, such as the European Commission, do not regard it as a prioritised issue in their environmental action plan. In 'Towards a Thematic Strategy on the Sustainable Use of Natural Resources' the European Commission (2003) claims: "At present the environmental impacts of using non-renewable resources like metals, minerals and fossil fuels are of greater concern than their possible scarcity. With fossil fuels, for example, it is the greenhouse gases from their use that are a pressing problem today rather than the risk of reserves running out." The EU strategic time horizon is 25 years. In the Millennium Ecosystem Assessment (2005), abiotic resources are not even on the agenda.

In SETAC's working group on impact assessment (Udo de Haes et al. 2002), abiotic resources are one of the main impact categories. Later in the UNEP/SETAC life cycle initiative (Jolliet et al. 2004), abiotic resources are further divided into Metallic minerals, Other minerals, Energy and Freshwater.

There is a broad consensus that impact category indicators in LCIA should represent significant environmental issues (ISO 2000), but there seems to be less consensus on how significant the problem of abiotic resource depletion is, and to what extent it should be on the agenda of LCIA. Should it be one category indicator representing the entire issue or several representing specific aspects?

The aim of this paper is to contribute to consensus-building on the use of category indicators for abiotic resources through identifying the expelled or implicit perceptions of the depletion problem that lie behind the indicators suggested today.

1 Review of Suggested Types of Indicators

For LCIA, various proposals have been made for impact categories and category indicators for abiotic resources. Several reviews are available, such as Lindfors et al. (1995), Guinée (2002) and Lindeijer et al. (2002).

In principle, there are four types of indicators:

- Those based on energy or mass
- Those based on relation of use to deposits,
- Those based on future consequences of resource extractions
- Those based on exergy consumption or entropy production

1.1 Energy and mass

To simply add all abiotic resources on the basis of mass or energy suggests that they are exchangeable and equally important with respect to their mass or energy content.

There seems to be little support for these types of indicators for LCIA. (Lindeijer et al. 2002).

1.2 Relation of use to deposits

Methods based on measures for use and deposits are discussed in Fava et al. (1993). The methods use various characterisation factors like 1/R, U/R and 1/R*U/R, where R is the mass of a specific resource and U is the present use of the resource. R could be ores that are identified reserves of concentrates that can be economically extracted or anticipated amounts of such concentrates or sometimes the total amount of a substance in the earth's crust as suggested by Guinée and Heijungs (1995).

Brentrup et al. (2002) suggests a similar approach, but it is to be used in the weighting phase, where they apply a distance to target model. Brentrup et al. estimate a target by making an assumption that the resources should last for a certain target time period such as 100, 300 or 1000 years and then determining the corresponding tolerable annual production. Their suggestion is basically the same as U/R, but multiplied by the target time period.

The design of these characterisation models indicates that there is no common idea of what a resource is and what substances to include. When category indicator results for different substances are added up, the total value will depend on how many substances are included. It also depends on how you group the resources. For example, if all fossil fuels are added together, an extraction of a certain amount of oil will have a lower category indicator result than if only oil reserves are considered.

There is an assumption about exchangeability of resources or at least that depletion of specific resources is a second order problem. Compared to the energy and mass-based characterisation, more weight is put on scarce resources. In case R refers to ores, the main interest is on the foreseeable future (some decades to a century). In case R is the amount of the substance in the earth's crust, there is no special time preference.

There seems to be a little more support for indicators based on use and deposits, than for only energy or mass types. Lindeijer et al. do not recommend it, but IAEA does (IAEA 2005). However, IAEA recommends it as an economic sustainability indicator and not as an environmental one. Similar thoughts are expressed by Guinée and Heijungs (1995), who find reserves and reserve base to be influenced too much by social contexts. They try to find the pure environmental aspect and therefore chose R to be the total amount in the earth's crust.

Guinée and Heijungs (1995) take the position that only extraction from the earth is of interest and ascribes the resources management in products and waste to the economic system.

1.3 Future consequences of resource extractions

The basic idea here is that extracting high concentration resources today will force future generations to extract lower concentration resources leading to an increased impact on environment and economy. Such indicators have been suggested by Weidema (2000), Steen (1999), Müller-Wenk (1999) and Stewart and Weidema (2005).

Weidema (2000) tests the idea of totally avoiding resources as a category indicator and assesses resource extraction in terms of the future increased impact in other impact categories. This seems to be possible, but would mean that if one found a way of extracting abiotic resources not impacting on the environment, no impact from decreasing deposits of abiotic substances would be registered.

Steen argues that most abiotic resources are not exchangeable. There is no environmental mechanism with a common node as in acidification (H^+) or global warming (IR-absorption) for different substances. Only for a single substance is there an exchangability, e.g. between copper ores of different grade. The characterisation factor for an ore reserve then becomes proportional to its concentration. The aggregation of different resources should be done in the weighting phase as it is a highly subjective matter. The weighting factor of an ore today is estimated from the increased cost for future generation to produce the same concentrates from a sustainable source, i.e. from bedrock. There is no temporal limitation in this view on resources.

Müller-Wenk (1998) looks at the increased energy requirement for future generations and argues that "If abiotic resources are considered to be scarce, the relevant question for a weighting model should therefore focus on the resource concentrations available in 100 or 1000 years from now, and less on the average crustal concentration which will 'never' be used for actual mining." He bases his category indicators on the increased use of energy when the total extracted metals are fivefold compared to the base year 1980. In practice, this may be expected to happen in a few hundred years.

Stewart and Weidema (2005) suggest a framework with focus on functionality measures and inclusion of man-made materials. They also want to define an ultimate quality limit for each resource and the future 'backup technology'. Although Stewart and Weidema do not express any specific time preferences, the use of functionality and ultimate quality limits seems to place the focus on the present society and the foreseeable future, i.e. decades to a century.

In the initial work in UNEP/SETACs life cycle initiative, there is a preliminary recommendation that "As a provisional starting point, the increase of energy requirements for future procurement of the currently used quantities per type of abiotic resource can be taken as a damage indicator. Surplus energy is used here as a proxy for the 'effort' needed to extract lower grade or lower quality resources. This energy requirement needs to be articulated in the context of the functionality required for each class of abiotic resources and as a function of technological evolution." (Jolliet et al. 2004)

1.4 Exergy consumption or entropy production

Processing abiotic resources requires energy. Finnveden (1994) has presented a method based on exergy use when producing the metal or substance wanted. He claims that exergy is the ultimate limiting resource because it has an associated energy cost that will be limiting to some extent when it becomes too high. He further argues that matter will not be depleted, but exergy will.

Aggregating resources in this way indicates a view that they are exchangeable and that if given enough economic resources we may extract what we need. No temporal restrictions are given for the concern of the depletion.

2 Different Ideas of the Problem with Abiotic Resources

In the short review given above, several aspects of the resource depletion problem have been brought forward. Below some of these will be discussed further.

2.2 The definition of abiotic resources

Resource depletion in itself is not a well-defined concept and differs somewhat from, for example, global warming and acidification in that the subjective elements stand out more strongly. The concept of resources is highly dependent on the presence of a user, the needs and skill of the user, expectations about the future and perceptions about what constitutes the depletion problem. Which resources and resource properties are valuable and need to be observed or preserved depends on what we think we or succeeding generations may need in the future.

The distinction between environmental aspects and economic aspects on resources is not clear. To some authors, the overlap does not seem to be a problem. If using LCA in a sustainability context, however, the overlap may lead to double counting.

2.3 Temporal focus

There are different ideas about which time perspective to apply. The European Commission developed a strategy with a 25-year perspective. Müller-Wenk (1998) writes: "Steen's approach can be criticized because there is no doubt that the necessity to switch to average earth crust materials in actual mining is extremely far away from now so that it is presumably not a concern of our society."

Some of the scenarios in Meadows et al. indicated a significant decline in human welfare somewhere between 2010 and 2020, but their model was made for the full century. If looking at the history of human cultures, the time scale becomes even longer (**Fig. 1**) and if regarding the human species, the perspective may be several million years. Using a cost oriented problem definition of abiotic resource depletion makes it natural to relate to present social contexts, but it is unfortunate if the low possibility to make accurate models of long-term abiotic resource depletion cost excludes these perspectives from the agenda.

2.4 Mining costs

The main sustainability threat in this type of resource characterisation is thought to be shortage of financial resources to produce the substances needed. This is a main feature in the World3 model used by Meadows et al. (2005).

A scenario like the one in **Fig. 2** may describe the depletion problem. In it, the concentration in the mined deposits decreases gradually and, sooner or later, the prices increase. In the beginning there may be a learning process, which may compensate for the cost of mining lower grade ores, but as the learning process levels out, there will be a net

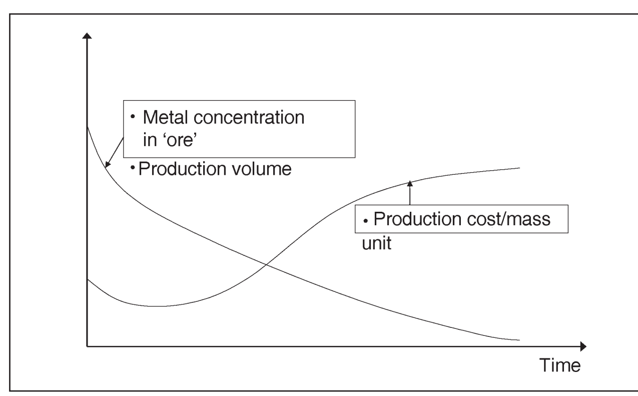

Fig. 2: Scenario for supply of metals from ores

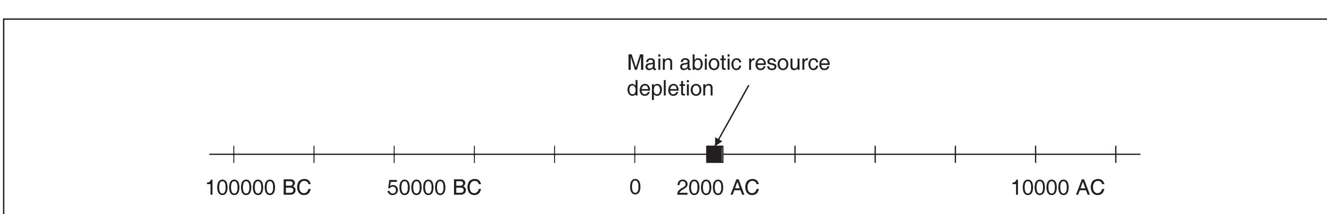

Fig. 1: Time perspective on abiotic resource depletion

Table 1: Best estimates of costs for production of ore-like metal concentrates compared with some current market prices for pure metals. P was not evaluated in the original work. It has been added later using the same method for cost calculation

Metal	Weighted average cost of 'ore' production EUR/kg metal	Today's price levels EUR/kg metal
Cd	68000	0.5–16
Co	260	8
Cr	140	8
Cu	160	1.7
Mn	5.60	0.5
Ni	250	6.8
Pb	390	0.6
Sn	1100	4.5
W	4800	0.03–0.2
Zn	44	0.9
P	3.8	0.3 (as P_2O_5-concentrate)

cost increase. As costs increase, use and production volumes will decrease. Ultimately, the production cost per mass unit will level out as we approach the average concentration in the crust of the earth.

Steen and Borg (2002) have calculated the production cost with current technology –made as sustainable as possible - for a number of metals when mined from bedrock, and compared it to metal prices (**Table 1**). Bedrock represents an average for the crust of the earth and is used as a reference because it is the ultimate reserve of many substances. For most elements, the amount available as ores is very low compared to the total amount in the crust of the earth. For instance, the Cu ores are only 0.01% of the total amounts in the crust of the earth (Skinner 1986).

An alternative to using cost estimates is to use physical parameters that are important for the cost estimates, such as concentrations and energy use in the production process, but such a method suffers to some degree from the same shortcomings as the cost estimate itself: it requires a process design or, as Stewart and Weidema puts it, a backup technology.

2.5 Shortage of energy

Processing abiotic resources requires energy. Finnveden (1994) has presented a method based on exergy use when producing the metal or substance wanted. He claims that exergy is the ultimate limiting resource because it has an associated energy cost that will be limiting to some extent when it becomes too high. He further argues that matter will not be depleted, but exergy will.

Is it likely that energy or exergy will be a limiting factor in the future? Exergy will ultimately be limiting as pointed out by Finnveden, but only on 'galactic scales'. As long as the sun shines on earth, there will be large amounts of energy available, and it seems more likely that our ability to collect and use it will be a limiting factor, or the presence of naturally stored sun energy in energyware, such as fossil fuels or wood.

In the early days of the steel industry, charcoal was used for production. This led to the depletion of large forests. If coke had not been invented as an alternative, a shortage of energyware would have resulted in decreasing iron production.

So energy or exergy for actual processes may be reasonable indicators, but, as pointed out by Finnveden (1994), the strongest motivation for using them is that they are cost related. Thus, there is a great similarity in problem definition to cost indicators and a meaningful focus and resolution in the choice of impact categories and category indicators are likely to be similar when mining cost is seen as the main problem.

2.6 Scarcity

The most common mental model of abiotic resource depletion seems to be that there is a limited amount given, which will be depleted. Although lower and lower grade ores may be included in this amount, sooner or later it will still be depleted and our main management option is to delay the depletion as long as possible. If this mental model is applied, the use rate and resource amounts will be of great interest.

If a substance is nearly depleted, i.e. R approaches zero, the expressions above may give very high values. However, the warning from such an indicator system may come too late if reserves are used as a measure for R. Only when use is large as compared to the resource, will there be a significant indicator response. Critics say that these figures always tend to be the same, since use and reserves are co-dependent. For simple economic reasons the searching for new deposits depends on the probability of exploitation. Guinée and Heijungs have suggested using the total amount available in the earth's crust as a measure for R.

2.7 Impacts from mining

The UNEP journal 'Industry and Environment' has had two special issues (1997) and (2000) on 'Mining and sustainable development'. Neither paid any attention to resource depletion. They concentrated entirely on impacts on land, impacts from emissions, and occupational health impacts.

In LCIA methodology, Ecoindicator 99 (Goedkoop and Spriensma 1999) uses anticipated added environmental impacts on human health and ecosystems (because of decreased future ore grades) as a measure of the environmental impact of resource extraction. They base their assessment on the method developed by Müller-Wenk (1998).

Guinée (2002a) argues that impacts on human health and natural and man-made environments from mining should be included through the inventory part of an LCA, as there are already impact categories for these areas of protection.

1.8 Integration in LCA

Besides different perception about the depletion problem, different use of the LCA tool may influence the way abiotic resource depletion is perceived and described. For abiotic resources, it is difficult to speak about an environmental mechanism in the same way as for global warming or acidification. In global warming and acidification, one substance may be replaced with another to give the same effect. For abiotic resources, there is no such mechanism. Some authors have suggested keeping category indicators for different abiotic resources apart when they are not exchangeable (Finnveden 1994, Steen 1999, Brentrup et al. 2002).

The optimal choice of category indicators for abiotic resources may largely depend on the goal and scope of the LCA study. If the study aims at characterisation at the midpoint level, it may be preferable with only a few category indicators for abiotic resources, while the number of indicators may be higher when weighting is used, as the weighting step allows further aggregation to more practical numbers of indicators.

3 Discussion

3.1 How important is the problem?

If the problem is increasing cost for utilisation of abiotic resources, it may be relevant to compare with damage costs for other impacts. In **Table 2**, the damage costs, as determined by the EPS 2000 method, are calculated for some global emissions and resource depletions. The damage cost for the most significant emissions is about 3% of the global GNP, while it is 10% for the resources. Using the more updated figures on Cu and P from Table 1 does not change these figures.

If damage cost calculated in this way were used as a measure of the significance of an impact category, there should perhaps be more abiotic resource impact categories than emission impact categories.

If the method suggested by Müller-Wenk is used, the ore-grade only drops with factors between 1.1 and 5, which gives an entirely different picture than that seen in Table 2. Damage costs for resources would then be more than two orders of magnitude less.

3.2 Accepting depletion

There seems to be a consensus in regarding abiotic resources as something that is subject to depletion or decreasing availability. This depletion is thought to be inevitable, and we can only influence the rate at which resources are depleted. There are, however, other options. One could regard abiotic resources as 'money in the bank' and decide to keep a certain amount 'saved up' for different types of crisis situations. Over the course of history, cultures have collapsed. Rebuilding a society requires readily available resources. To save abiotic resources 'in the bank', we would have to change our use of them radically. Most people would not consider this to be realistic, but it could have some value as a mental model for sustainable development in relation to abiotic resources. It can hardly be denied that a society with more abiotic reserves is more sustainable than one with less reserves. The restoration costs as described in Table 1 represent a measure of the value of the reserves.

The restoration cost may decrease in the future as alternative technologies are developed. For instance, some elements may be collected when large biomass flows are processed, for example from green liquor sludge in kraft pulp mills or ashes from biomass burning. Once the long-term value of

Table 2: Weighted global emissions and resource depletions for 1990 as determined by the EPS default method (Steen 1999). 1 ELU corresponds to 1 EUR

Substance	Global emission or reserve depletion, kg/year	EPS default index, ELU/kg	Added global value (EUR)	% of adjusted global GNP
CO_2	2.20E+13	0.108	2.38E+12	2.24
SO_2	1.70E+11	3.27	5.56E+11	0.52
NO_x	1.53E+11	2.13	3.26E+11	0.31
Fossil oil	3.40E+12	0.506	1.72E+12	1.62
Fossil coal	3.17E+12	0.0498	1.58E+11	0.15
Natural gas	1.56E+12	1.1	1.72E+12	1.62
Ag-ore	1.30E+07	54000	7.02E+11	0.66
Al-ore	2.11E+10	0.439	9.26E+09	0.01
Au-ore	1.46E+06	1.19E+06	1.74E+12	1.64
Cu-ore	9.03E+09	208	1.88E+12	1.77
Fe-ore	5.07E+11	0.961	4.87E+11	0.46
Pt-ore	1.24E+05	7.43E+06	9.21E+11	0.87
Pd-ore	9.90E+04	7.43E+06	7.36E+11	0.69
Pb-ore	2.80E+09	175	4.90E+11	0.46
P-minerals	1.73E+10	4.47	7.73E+10	0.07

abiotic resources is recognised and established in society, there will probably be a number of alternative methods for producing high concentrates from dilute sources. But it may be debated if any of these future developments should be accounted for now.

4 Conclusions and Recommendations

The line that divides the perceptions of the mineral resource problem most is the time perspective applied. If only safeguarding the next decades or century, the mineral resource problem is one among others. If applying historical perspectives with tenths of thousands of years, the problem becomes huge.

Another dividing line is the ambition to separate environmental and economic aspects and yet another is how much of the consequences of decreased availability that should be part of the LCI and how much should be part of the impact assessment.

Today there seems to be some consensus on developing the 'future consequence' alternative further with consideration to resource functionality.

Many authors seem to have a fairly optimistic view on our ability to cope with resource depletion and see substitution, recycling and general development of economy and technology as efficient means for resource housekeeping. However, there is a danger in incorporating this kind of thinking in the LCA method. The LCA method is supposed to give signals and advice to develop technology in a sustainable direction, not to assume it will happen by itself.

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